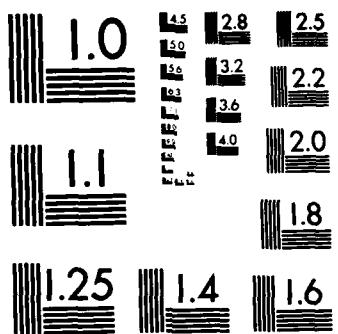


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OF ASTROPHYSICAL PLANETARY AND A M V GOLDMAN
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Final Report: October 1, 1983-September 30, 1985

**"Plasma Wave Turbulence and Electromagnetic Radiation Caused by
Electron Beams"**

Martin V. Goldman, Principal Investigator

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)
Research was completed on a program to understand the mechanisms by which mildly relativistic electron beams can generate microwave radiation when injected into plasmas. The chief phenomena found to be involved were (1) stimulation compton conversion of Langmuir waves excited by relativistic e⁺beams and (2) multiple Raman up-conversion of radiation from pre-existing Langmuir turbulence. Numerical programs were developed for computing the evolution of beam-excited Langmuir waves into strongly turbulent states. It was further, experimentally determined that "quiet" plasmas with low level of ambient density fluctuations were necessary in order to obtain optimum radiation. Six archival publications, two PhD theses, and three invited papers resulted from this work.

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Abstract

This final report covers theoretical, numerical, and experimental research performed from October 1, 1983 to September 30, 1985 on the topic: fundamental turbulence properties of plasmas irradiated by relativistic and nonrelativistic electron beams, and emission of high-frequency radiation from such systems.

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I. Summary of Accomplishments under AFOSR Grant #84-0007

Between October 1, 1983 and September 30, 1985 we completed a multifaceted research project concerning turbulence and electromagnetic emission in electron-beam plasma systems. This was the final period in a sequence of research programs which had been in effect under AFOSR auspices since August 1976, preceded by support from Kirtland AFB between 1972 and 1976.

We have performed studies in three inter-related areas:

- A. High frequency radiation due to electron beams (see publications in Section II.A. 3,4 and thesis II.B.1).
- B. Plasma turbulence excited by electron beams (see II.A.1,2,5,6 and thesis II.B.1).
- C. Laboratory experiments on beam plasma systems (see thesis II.B.2).

This research resulted in six publications, two completed Ph.D. theses at the University of Colorado at Boulder, and three major invited papers at international technical conferences (see Section II.C).

Two different mechanisms for the emission of higher frequency electromagnetic radiation were analyzed: stimulated Compton conversion of Langmuir waves excited by relativistic electron beams (II.A.3, II.B.1), and multiple Raman up-conversion of radiation from pre-existing Langmuir turbulence (II.A.4). Both of these studies were motivated by the discovery that megawatts of emitted radiation at frequencies up to at least 30 gigahertz could be generated by firing mildly relativistic electron beams into pre-ionized plasmas.¹

Stimulated inverse Compton conversion in which a Langmuir wave scatters off a relativistic electron while converting into a transversely polarized electromagnetic wave was considered by a Ph.D. student, David Newman, as a means for producing amplified electromagnetic radiation from a beam-plasma

system at frequencies well above the electron plasma frequency. The stimulated emission growth rates of the radiation produced by a monoenergetic ultrarelativistic electron beam were determined as a functional of the Langmuir turbulence spectrum in the background plasma and numerically evaluated for a range of model Langmuir spectra. Growth rates for this process appear to be too small to account for the intense high-frequency radiation observed in the laboratory experiments.¹

An alternative way to produce radiation at frequencies much above the plasma frequency was explored by Russell, Goldman and Newman (II.A.4). In this mechanism, one begins with radiation already produced at the fundamental or second harmonic, and allows it to Raman scatter repeatedly from pre-existing Langmuir turbulence, produced along with the primary radiation by an external source, such as an electron or laser beam. At each step, such scattering leads to frequency upshifts and downshifts. The resulting radiation spectra was found to exhibit frequency components significantly above the plasma frequency. Favorable comparisons were made with laser-irradiated plasmas.

Both of the observed mechanisms for producing radiation depend strongly on the spectrum of Langmuir waves (electron plasma waves) excited by the electron beam or other external source. Hence, it is critical to understand the fundamental properties of beam-excited Langmuir turbulence. We have performed pioneering theoretical studies of observed turbulent phenomena such as modulational instability² and phase-coherent wave self-focusing.³⁻⁶ The emerging new subject goes under the general name of 'strong turbulence,' and has formed a major component of our research. A comprehensive review of our work in this area can be found in the review article, "Strong turbulence of plasma waves," by the principal investigator, M. Goldman (II.A.2, also see II.A.6), based on an invited paper delivered before the Plasma Physics Division

of the American Physical Society (II.C.1).

Numerical programs were developed for computing the evolution of beam-excited Langmuir waves into strongly turbulent states. Energy densities, spectral shapes, and physical mechanisms have been identified over a wide variety of parameters. Simplified models have enabled us to study Langmuir wave envelope soliton formation and chaotic intermittency (II.A.1,5,6).

In addition to theory, we completed an in-house experimental program, with the help of Prof. R. Stern, an experimental plasma physicist at the University of Colorado, and a Ph.D. student, J. Casey, whose thesis on "The Role of Three-Wave Scattering in the Saturation of Electron-Beam Driven Langmuir Waves" was completed under AFOSR sponsorship. In this work, low energy electron beams were launched into controlled plasma targets containing pre-formed ion-acoustic turbulence designed to optimize the efficiency of electromagnetic emission. Beam-driven Langmuir waves were observed directly. An introduction of ion-acoustic turbulence was found to suppress the intensity of the Langmuir waves due to stimulated scattering, thus underscoring the necessity of "quiet" plasmas with a low level of ambient density fluctuations for optimum radiation.

Our research on beam excited Langmuir turbulence has general significance. A wide variety of electron-beam sources in the laboratory^{1,5,6} and interplanetary space^{3,7} excite plasma instabilities. In all these applications the excited waves saturate into a turbulent spectrum and can heat the plasma, accelerate selective plasma particles, and affect the propagation of the ionized beam, as well as expedite the emission of radiation.

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II. Publications, theses and major presentations between 10/1/83 and 9/30/85

A. Publications of work performed under AFOSR sponsorship between 10/1/83 and 9/30/85

1. H.T. Moon and M.V. Goldman, "Intermittency and Solitons in the Driven Dissipative Nonlinear Schrödinger Equation," *Phys. Rev. Lett.* **53**, 1821 (1984).
2. M.V. Goldman, "Strong Turbulence of Plasma Waves," *Rev. Mod. Phys.* **56**, 709 (1984).
3. D.L. Newman, "Stimulated Compton Conversion of Langmuir Waves by Relativistic Electron Beams," *Phys. Fluids* **28**, 1482 (1985).
4. D. Russell, M. Goldman, and D. Newman, "Multiple Raman Up-Conversion of Radiation from Pre-Existing Langmuir Turbulence," *Phys. Fluids* **28**, 2162 (1985).
5. G. Pelletier, M. Goldman, H.T. Moon, and W. Merryfield, "Autonomous Dynamical Systems Arising from Self-Similar Parameterization of Damped/Driven NLS Equations," *Physica* **18D**, 154 (1986).
6. M.V. Goldman, "Langmuir Wave Solitons and Spatial Collapse in Plasma Physics," *Physica* **18D**, 67 (1986).

B. Ph.D. theses completed under AFOSR sponsorship (10/1/83-9/30/85)

1. David Leonard Newman, "Emission of Electromagnetic Radiation from Beam-Driven Plasmas," Doctoral Thesis, University of Colorado (1985).
2. Jeffrey Allen Casey, "The Role of Three-Wave Scattering in the Saturation of Electron-Beam Driven Langmuir Waves," Doctoral Thesis, University of Colorado (1985).

C. Invited papers at major conferences (10/1/83-9/30/85)

1. "Strong Langmuir Turbulence: Theory and Application to Space and Laboratory Experiments," M.V. Goldman, presented at the annual meeting of

the Plasma Physics Division of the American Physical Society, Los Angeles, November 1983.

2. "Strong Langmuir Turbulence," M.V. Goldman, presented at the Joint US-Japan Workshop on Statistical Plasma Physics, Nagoya, Japan, February 1984.
3. "Solitons and Chaos," M.V. Goldman, presented at the Institute for Theoretical Physics, Santa Barbara, January 1985.

D. Contributed Talks (10/1/83-9/30/85)

1. "Multiple Raman Up-Scatter of Radiation in Turbulent Plasma," D. Russell, D. Newman, and M.V. Goldman: paper 2T12, Bull. Am. Phys. Soc. vol. **28**, pg. 1068, November 1983 (Los Angeles meeting of the Plasma Physics Division of the American Physical Society).
2. "Induced Compton Up-Conversion of Langmuir Waves by a Relativistic Electron Beam," D. Newman: paper 9U7, Bull. Am. Phys. Soc. vol. **28**, pg. 1068, November 1983 (Los Angeles meeting of the Plasma Physics Division of the American Physical Society).
3. "Ion Extraction by Driven Electrostatic Ion Cyclotron Waves," R.A. Stern, Bull. Am. Phys. Soc. vol. **28**, pg. 1078, November 1983 (Los Angeles meeting of the Plasma Physics Division of the American Physical Society).
4. "Ion Dynamics of Current-Driven Ion Cyclotron Waves," D.N. Hill, R.A. Stern, and N. Rynn, Bull. Am. Phys. Soc. vol. **28**, pg. 1105, November 1983 (Los Angeles meeting of the Plasma Physics Division of the American Physical Society).
5. "Particle in Cell Simulation of Driven Langmuir Collapse in Two Dimensions," M.V. Goldman, D.A. Russell, D.W. Forslund, and D.F. DuBois, paper 3Q8, Bull. Am. Phys. Soc. vol. **29**, pg. 1237, November 1984 (Boston meeting of the Plasma Physics Division of the American Physical Society).
6. "Intermittency, Chaos and Solitons in the Driven Dissipative Cubic Schroedinger Equation," H.T. Moon and M.V. Goldman, paper 1Q11, Bull. Am. Phys. Soc. vol. **29**, pg. 1182, November 1984 (Providence meeting of the Fluid Mechanics Division of the American Physical Society).

7. "Self-Similar Solutions to Nonlinear Schroedinger Equations," G. Pelletier and M.V. Goldman, paper 3Q13, Bull. Am. Phys. Soc. vol. **29**, pg. 1238, November 1984 (Boston meeting of the Plasma Physics Division of the American Physical Society).
8. "Caviton Collapse in a One-Dimensional Model of Langmuir Trubulence," D. Russell, D. DuBouis, H. Rose, and M.V. Goldman, paper 3Q7, Bull. Am. Phys. Soc. vol. **29**, pg. 1237, November 1984 (Boston meeting of the Plasma Physics Division of the American Physical Society).
9. "Electron BEam Plasma Instability in the Presence of Ion Acoustic Turbulence," J. Casey, R. Stern, and M. Goldman, paper 1W1, Bull. Am. Phys. Soc. vol. **29**, pg. 1197, November 1984 (Boston meeting of the Plasma Physics Division of the American Physical Society).
10. "The Role of Three-Waves Scattering in the Saturation of Electron Beam Driven Langmuir Waves," J.A. Casey, R. A. Stern, and M.V. Goldman, paper 5R7, Bull. Am. Phys. Soc. vol. **30**, pg. 1501, November 1984 (San Diego meeting of the Plasma Physics Division of the American Physical Society).

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